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The need for policies to reduce the costs of cleaner cooking in low income settings: Implications from systematic analysis of costs and benefits

Marc Jeuland[a,d,*], Jie-Sheng Tan Soo[b], Drew Shindell[c]

[a] Sanford School of Public Policy and Duke Global Health Institute, Duke University, Box 90239, Durham, NC 27708, USA
[b] Lee Kuan Yew School of Public Policy, National University of Singapore, 469B Bukit Timah Road, Singapore 259771, Singapore
[c] Nicholas School of the Environment and Duke Global Health Institute, Duke University, Box 90328, Durham, NC 27708, USA
[d] RWI-Leibniz Institute for Economic Research, 45128, Essen, Germany

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ABSTRACT

Inefficient household cooking in less-developed countries harms health and productivity, the environment, and the global climate. Interventions to encourage adoption of cleaner and more fuel-efficient stoves are being implemented widely to reduce these burdens, but sustained use has proven elusive. This study develops a data-driven simulation approach to investigate the potential costs and benefits of cleaner stoves, informed by recent empirical studies. The results suggest that the private case for adoption of technologies other than charcoal ICS is often unclear; that is, households' private benefits do not usually outweigh the costs of these improvements. Overall social benefits, in contrast, are typically positive and large for nearly all such improved technologies. We investigate how economic benefits vary with intensity of use, and find that higher use does not unambiguously translate into greater private benefits. Analyzing the effects of different subsidies, we further find that fuel subsidies for purchased fuels could substantially improve private net benefits, but that even these may be insufficient to make cleaner cooking attractive to many households; stove subsidies meanwhile tend to modestly improve private outcomes. To capture the social benefits of cleaner cooking, new and effective incentives may be needed to support household use of efficient stoves.

1. Introduction

About three billion people rely on a toxic combination of solid fuels and inefficient stoves to meet their daily household cooking and heating needs. These households inevitably incur significant health and productivity costs, and impose serious environmental damages at regional and global scales (Anenberg et al., 2013; Lim et al., 2013; Smith et al., 2013). In particular, pollution emitted from inefficient stoves burning solid fuels is responsible more than 4 million deaths each year and accounts for about 25% of global emissions of black carbon (BC) – an extremely potent climate forcer in the short term (Lim et al., 2013; Martin et al., 2014; Myhre et al., 2013). Meanwhile, unsustainable solid fuel harvesting damages forest ecosystems (Bailis et al., 2015). In light of these negative effects, increasing attention and resources are being directed towards interventions that develop and distribute cleaner improved cookstoves (ICS) to poor households.[1] Yet important questions remain about who should pay for the improved technologies and whether it makes sense for households to adopt and use potentially more expensive stoves and fuels (Jeuland et al., 2015).

The literature on the economics of ICS often argues that the private net benefits (health, productivity, and fuel savings) provided by such technologies are large even without including environmental benefits, and that household should therefore adopt them. For example, one recent study that included only private benefits (health, time and fuel savings) estimated that the annual global net benefits of switching from traditional to various improved cookstoves (ICS) reaches between US $18 and US$54 billion (Larsen, 2014). Earlier cost-benefit analyses projected similarly large net benefits, also noting that ICS adoption was cost-saving for households (Hutton et al., 2007).

Importantly, such calculations are hard to reconcile with the reality of highly varied demand, use, and impacts of ICS technologies following promotion in many settings. Numerous examples exist – in both the distant and recent past – of dissemination programs and demand studies that have demonstrated low demand over the short and medium term

* Corresponding author.
E-mail address: marc.jeuland@duke.edu (M. Jeuland).

[1] We use the term improved cookstove (ICS) to refer to a large range of technologies, specifically those that appear in the Global Alliance for Clean Cooking (GACC) clean cooking catalogue plus other published studies that claim to consider improved options. We acknowledge that the term ICS has become controversial, but explain the reasons for applying this inclusive definition in Section 2.

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(Barnes et al., 1994; Bensch et al., 2015; Cundale et al., 2017; Gall et al., 2013; Hanna et al., 2016; Mobarak et al., 2012; Ruiz-Mercado et al., 2011). While innovative promotion experiments developed to address classical problems of technology adoption (e.g., informational and liquidity constraints, present bias, lack of female bargaining power) have demonstrated higher demand (Beltramo et al., 2015; Levine et al., 2018; Pattanayak et al., 2018), as well as impacts on livelihoods (Bensch and Peters, 2013, 2015; Beyene et al., 2015; Pattanayak et al., 2018), these more favorable results remain somewhat limited. At first glance, the results of the bulk of the studies' that contradict the global cost-benefit calculations are puzzling, and firstly suggest that households in many low-income settings are not making forward-looking decisions. An alternative supposition, which we explore in this paper, is that these prior net benefits calculations are perhaps somewhat misleading. For example, they may rely on inconsistent or incomplete valuation measures, may be based on studies conducted in locations or with technologies for which net benefits are most likely to be positive, or may make optimistic assumptions about the ways people use and benefit from technology, for example ignoring learning or adaptation costs (Bensch and Peters, 2015; Gebreegziabher et al., 2018). In addition to these shortcomings, it is worth noting that analyses pointing to high net benefits are largely deterministic and underappreciate real world variability in costs and benefits (Whittington et al., 2012).

This study attempts to address these shortcomings by applying evidence from the burgeoning empirical literatures on the exposure-health, climate, and social sciences aspects of this problem. We use this evidence to derive new estimates of the net benefits of switching from a traditional stove to various ICS, to compare the consistency of deterministic and probabilistic results, and to derive insights on the role of fuel and stoves subsidies in promoting adoption and usage of various types of ICS. The basic approach is implemented as follows, building from a methodology described by Jeuland and Pattanayak (2012). We start from a typology of the costs and benefits of adoption of ICS, distinguished by stove-type and fuel. The included benefits are health – morbidity and mortality reduction, and health spillovers from better ambient air quality; productivity, or time savings; and environmental – reduced climate forcing and deforestation. Costs include technological and program costs; operation, maintenance, and fuel costs; and learning. Next, these various costs and benefits are represented by valuation equations specified on the basis of the latest scientific and economic research. Third, we comb the literature in relevant fields to specify plausible real-world variation in each of the roughly thirty parameters appearing in these equations.[2] Finally, we run 10,000 Monte Carlo simulation trials to generate ranges and distributions of net benefits for each ICS. Because the parameters have been sourced from the literature, we believe that the outcome distributions reflect the variation that is likely to exist in developing countries; importantly we can further study this variation to obtain insight on which parameters are most influential in affecting the simulated outcomes. Still, we emphasize that the frequency with which any specific combination of parameter values – or net benefit outcomes – would arise is unknown. This may be important due to the site- or intervention-selection bias (Allcott, 2015) that may exist in field research or reports on ICS issues.[3] Thus, our outcome distributions should not be interpreted to represent the precise distribution of real-world outcomes. Indeed, the major shortcoming of our approach is that the simulations may create combinations of stove characteristics that one does not often find in the real world, though the direction of any bias that might result from this issue is unclear.

All categories of costs and benefits are expressed in present value terms, with future costs and benefits discounted using an exponential discount function. This logic applies for the climate benefits as well. Hence, we derive a time-varying radiative forcing for each climate-altering pollutant produced by different cookstoves to compute a present-value discounted global warming impact for each technology (Shindell, 2015).

To build intuition on the importance of various categories of costs and benefits, we first compare results when all parameters take on the average model values, before presenting the Monte Carlo simulation results. We show: 1) The private net benefits of ICS adoption (Private); 2) A narrow definition for social net benefits (Social), which includes private benefits plus health spillovers and averted deforestation and relevant Kyoto protocol pollutants (carbon dioxide, methane and nitrous oxide); and 3) A more complete definition for social net benefits (Social +), which adds changes in emissions of other important climate-altering pollutants (BC, carbon monoxide (CO), non-methane hydrocarbons (NMH), and organic carbon (OC)) (IPCC, 2013). BC in particular is a powerful positive forcer produced in abundance by residential biomass fuel burning (Bond et al., 2013). We briefly discuss sensitivity analyses that provide insights on which parameters drive variation in the simulation results.

Finally, we analyze how the distributions of private net benefits for the socially most beneficial technologies shift as a function of: 1) use of the improved option; 2) subsidy for purchase of a cleaner stove; and 3) subsidy for purchase of the fuel required by that stove. The purpose of the former analysis is to explore the importance of the intensive margin of adoption for altering net benefits, given that households can clearly optimize behavior on this margin. The latter two analyses then shed light on the extent to which two specific price instruments are helpful in making private use of cleaner technologies attractive to utility-maximizing households. We can also compare the likely relative effects – on private net benefits – of fuel vs. stove subsidies. While it is obviously true that subsidies will increase the private net present value (NPV) of a switch to cleaner ICS technologies, we show that it is very much an empirical question whether such measures are sufficient to make them attractive (i.e., private NPV > 0), given real world heterogeneity in cooking conditions and constraints.

2. Methods and data

Our model compares the costs and benefits of households' switching from traditional stoves to various alternatives – thus, the NPV we calculate assumes that a household adopts the new technology. In other words, we abstract away from the extensive margin of adoption. This is useful in illuminating whether a decision to adopt can be considered rational, from the household and social perspective. Most modeled transitions are from a traditional firewood stove, except for charcoal,

[2] These parameters include aspects related to stove and fuel prices and other characteristics (longevity of stoves, time and thermal efficiencies, fuel calorific content); maintenance and promotion program costs; behavioral parameters (cooking time, fuel needs and collection time, stove use rates); baseline health conditions (incidence or prevalence of, and mortality from, diseases related to household air pollution); emission rates and the climate and health effects of emissions; and valuation parameters for time savings, health and environmental consequences.

[3] Several dimensions of potential selection bias deserve mention here, although we admit that we are not aware of work documenting their existence in this context. The technologies studied by researchers, or discussed in grey literature produced by NGOs, donors, or international organizations such as the Global Alliance for Clean Cookstoves (GACC), may be systematically different from those deployed in the real world. In addition, our primary source for stove characteristics – which is supplemented by information in specific research studies – is the GACC stove catalogue, which may itself contain technologies that are systematically different from those studied by researchers (in terms of aspects such as efficiency, beneficiary usage, etc.). In particular, it seems possible that stoves studied in the field are more efficient than the options that are generally available to households, because most ICS research has been focused on health. It is also possible that study sites may be selected to produce positive outcomes (since researchers usually prefer to avoid null or negative results), though bias in the opposite direction also seems possible (for example if researchers focus on remote or other low demand contexts, or on unproven technologies). We are unaware of evidence suggesting a systematic bias towards more or less favorable sites, but this issue is worthy of additional investigation.

Table 1
Typology of costs and benefits of cooking transitions (adapted from Jeuland and Pattanayak, 2012).

Costs	Examples	Benefits	Examples
Privately borne; included in analysis			
Capital ("hardware")	Cost of new technologies: Improved cookstoves; ventilation / cooking space improvements; etc.	Morbidity & mortality reductions (direct)	Benefits from reduced incidence of and mortality from disease (acute respiratory infections (esp. ALRI); COPD; lung cancer, IHD)
Program ("software")	Cost of implementation/delivery: Marketing and promotion materials; NGO/government staff time; etc.	Time savings	Benefits of reduced cooking time (due to more efficient heating)
Operation and maintenance	Cost of replacing / cleaning of equipment, including time		
Fuel used in new stove	Cost of fuel, in collection and preparation time and/or money	Fuel no longer used in old stove	Cost of fuel, in collection and preparation time and/or money
Learning and tastes	Costs of familiarization with the use of a new stove technology; loss of value from modified taste		
External to household; included in analysis			
		Spillover morbidity & mortality reductions	Benefits from reduced incidence of and mortality from above diseases due to reduced ambient pollution
		Climate- and ecosystems-related	Benefits from reduced emissions of black carbon and decreased tree cutting
Costs and benefits not included in the analysis: Health benefits from reductions in conditions other than ALRI, COPD, lung cancer and IHD, and from reductions in pollutants other than $PM_{2.5}$; morbidity reduction benefits not included in cost-of-illness measures; aesthetic benefits from cleaner options; benefits from reduced loss of ecosystem services; benefits of reduced risk of violence during fuel harvesting; costs from inconvenience / taste problems / loss of heat or insect control; and changes in energy security (could be costs or benefits).			

Notes: Grey-colored cells correspond to those for which the calculation of private and social values is different, due to differences in discounting of upfront capital and learning costs, given that private discount rates diverge from social ones.

since users of charcoal ICS typically transition from traditional charcoal options. The unit of analysis is the individual household; costs are compared with benefits on a per household-month basis. We compare the economic attractiveness of the different stove alternatives relative to the baseline of unimproved biomass-burning stoves using a net benefits criterion (Boardman et al., 2005). We conduct our assessment from both a private and a social welfare perspective, and whenever possible, use welfare-theoretic (not income) measures of benefits and costs.

2.1. Model costs and benefits

Switching to a different cooking technology entails a variety of costs and benefits (Table 1). Costs include capital investment, program expenses from distributing stoves, operation and maintenance (O&M), the change in net fuel cost and learning. Benefits include improved health and cooking time savings (mostly private), plus climate-related environmental benefits to society, from reduced black carbon or greenhouse gas emissions and deforestation (Table 1). For the private perspective, only the costs and benefits accruing directly to households are included. We assume that households internalize all non-pecuniary benefits (e.g., reduced sickness, time savings).[4] Thus, only the social perspective includes health spillovers, and effects on climate-altering emissions and forest loss. Total costs and benefits are the sum of these components, and we assume that these accrue to households as a function of use. The equations that underlie the calculations of each of these categories are explained in detail in the Supplementary materials.

2.2. Key model assumptions

As in any such model, our CBA simulation tool rests on a variety of assumptions. We describe what we see as the most consequential such assumptions here; additional details appear in the supplement.

The first major assumption concerns the specific ICS technologies included in the analysis. Here we adopt an inclusive definition for what constitutes as "improved". We start with the list of stoves in the GACC Clean Cooking Catalogue (http://catalog.cleancookstoves.org/) that have useable data on at least one model parameter, and supplement this list with any additional technology with similar data that appears in the broader ICS literature (see Section 2.3 for details on the search procedure we use to source from the literature). Some may object to this inclusive approach (as well as to our inclusion of kerosene), and argue that we should only analyze technologies that meet specific standards. Exclusion of specific options creates significant conceptual and practical difficulties, however. For one, we do not believe that there is general consensus on what constitutes "improved". Many refer to the IWA Tier ranking system (Still et al., 2015), yet some believe that Tier 2 is an important improvement while others argue that even Tier 4 is not sufficiently clean. From a practical perspective, it is also difficult to

[4] If anything, this makes our "private" perspective optimistic about the NPV households would perceive. As a reviewer pointed out, there is ample empirical evidence to show that households may not fully internalize non-pecuniary benefits, though we do assume that the value of time saved would be below the market wage.

categorize the majority of available alternative technologies according to this IWA system, due to limited testing. In addition, technological features may come with tradeoffs that are not entirely evident when sourcing parameters from the literature as we do. More efficient stoves may have other negative features (low useability, or high cost), and vice versa. Excluding specific technologies from our study would raise important concerns about bias in our simulation results (choosing only the "best" combinations of parameters, regardless of whether they even coincide in the real world). Overall, we believe that our approach is adequate in characterizing the relevant range of low and high performance stoves. Finally, our one-way sensitivity analyses allow readers to see the effect that specific consequential parameters have in shifting the NPV distributions; many of these do in fact relate to the ICS characteristics.

A second major set of assumptions relate to the costs and benefits included in the model, and their associated valuation parameters, for which cross-setting data are sparse. Time costs (and benefits) are valued at a fraction of the unskilled market wage that is allowed to vary, to reflect the lower opportunity cost for time spent cooking or gathering fuel relative to work time (Jeuland and Pattanayak, 2012). Our costs do not account for the fact that many stoves may be inconvenient, for a range of reasons related to taste preferences and heating or other needs (Jeuland et al., 2015). Similarly, they do not account for aesthetic non-health benefits of clean stoves.

Third, with regards to health benefits, our model only includes the four diseases for which the most compelling evidence exists (acute lower respiratory illness, chronic obstructive pulmonary disease, lung cancer and ischemic heart disease), and omits the effects of pollutants other than $PM_{2.5}$ (Smith et al., 2013; Zhang and Smith, 1999). We assume that mortality decreases due to reduction in exposure to $PM_{2.5}$ (itself a function of stove emissions and an exposure fraction) according to the relationships in the integrated exposure response function (Burnett et al., 2014), rather than using evidence from the very limited number of ICS health effects trials (Mortimer et al., 2017). We further assume that the relative risks of morbidity for those exposed are reduced similarly to those for mortality, since Burnett et al. only discuss mortality risk (Burnett et al., 2014). Estimates of health spillovers from ambient air quality improvements are based on their estimated contribution to the burden of disease (Chafe et al., 2014), and do not account for differences in ambient air quality across settings. Risk of violence and injury during fuel collection is also not included. The health valuation concepts we use are the avoided cost-of-illness (COI) per case or per year for morbidity, and the value of a statistical life for reduced mortality (Viscusi and Aldy, 2003).

Fourth, we value environmental benefits using the social cost of carbon (Interagency Working Group on Social Cost of Carbon, 2015) for non-CO_2 emissions converted to temporally-consistent (discounted) carbon dioxide equivalents based on global mean temperature impacts (Shindell, 2015). Additional benefits accruing from BC reductions related to decreased disruption of traditional rainfall patterns or melting associated with BC deposited to snow and ice surfaces are not included, making our estimates likely conservative. We also use the replacement cost for trees, for deforestation and forest degradation. However, this replacement cost for trees omits valuation of ecosystem services lost due to the lack of data (Ferraro et al., 2011). For LPG, kerosene, and also electric options, we do not value the energy security implications of (potentially) greater reliance on fossil energy sources (Bohi and Toman, 2012).

Finally, in the private analysis, we apply a range of constant discount rates that is consistent with market evidence on the private rate of time preference (with a lognormal distribution that effectively ranges between 7% and more than 100%), while the social analysis uses a much lower social discount rate that varies from 1% to 6%.

2.3. Data and model parameterization

In order to estimate the costs and benefits of switching technologies, we reviewed the literature to specify a range and distribution of possible values for the parameters that appear in the model equations. The search process for this review began with selection of sets of key terms for identifying academic papers from two major search engines (Econlit and Google Scholar). For example, when searching for parameters typically measured in evaluations of promotion programs, we started with the following combination of terms: ("stove" OR "cookst*") AND ("interventi*" OR "program*"). Given that our purpose was not a systematic review, search strings were deliberately specified in broad terms initially. These were then modified iteratively – by omitting and adding search terms – as needed when looking for parameters that were relatively infrequently discussed in the general literature on improved cooking (e.g., specific types of emissions parameters, parameters on discount rates, or real-world time savings).[5] Furthermore, because the model is envisioned to reflect real-work heterogeneity in many different types of parameters, our search approach was kept as inclusive as possible.

The initial search yielded an extensive and diverse set of references written from a variety of disciplinary perspectives. These peer-reviewed articles, reports, books and working papers were scanned for the type of quantitative data we needed, and those that offered usable parameter values were retained, and relevant information was recorded in our database (see Supplementary materials). We further supplemented the database by conducting forward and backward searches of citations from the most prominent retained studies, especially those published in top disciplinary journals or reports issued by reputable agencies with extensive investments in clean cooking (e.g., GIZ, World Bank, GACC). Most (76%) of the retained sources are peer-reviewed journal articles, and the geographic, technological, and temporal coverage of these sources is generally good (Table 2 provides a summary of counts pertaining to these references).[6] Nonetheless, we acknowledge that the underlying data in our model remains incomplete, because the literature on relevant parameters is highly fragmented and growing quickly.

To parameterize the model, we generally chose lognormal distributions for the analysis when we had at least 40 data points. A special class of such parameters was obtained from country-level datasets, these were weighted by country populations to yield a re-weighted global mean. For parameters with fewer data points, we used uniform distributions that were extended when uncertainty was deemed especially great (specifically, doubling the span of the range or the upper bound in specific cases, as noted in the Methods SI). The parameters for which we find the least evidence are the following: Electric and kerosene stove costs, maintenance/adaptation costs, wood fuel purchase rates, and time efficiencies and emissions factors for some stove-fuel combinations. The social cost of carbon (SCC) parameter was treated differently: we applied a triangular distribution with bounds corresponding to the average 5th, 50th, and 95th percentile estimates across Integrated Assessment Models used by the Interagency Working Group. We also expressed this SCC parameter (and the bounds on its distribution) to be an exponential function of the discount rate, consistent with theoretical arguments. Finally, we specified likely correlations between parameters (e.g. stoves with long lifespans are likely to cost more) to avoid putting undue emphasis on what may be particularly unlikely combinations of model parameters (though we note that these assumptions have a relatively limited influence on our results, as discussed further below). For each parameter, all underlying data and model assumptions are documented in the Supplementary appendix.

[5] For example, for time efficiency of charcoal stoves, we altered the search string to: ("stove" OR "cookst*" OR "fuel") AND ("charcoal") AND ("time").

[6] Technological coverage is important because we aim to specify parameters that are specific to each ICS technology (natural draft biomass, forced draft biomass, charcoal, LPG, kerosene, and electric), whenever possible.

Table 2
Counts of articles supplying parameters included in the model database.

Characteristics	Types of parameters obtained									
	Cooking practices	Fuel costs/ availability	Stove adoption/ characteristics	Stove efficiency	Emissions	Health conditions & impacts	Forest/fuel collection	Valuation parameters	Other	All
Study type										
Peer-reviewed article	21	17	22	25	43	26	9	22	19	135
Book or book chapter	0	0	0	0	0	3	0	0	0	3
Working paper	5	4	4	2	3	3	1	8	4	19
Report	0	4	1	0	3	6	1	4	8	20
Discuss any ICS, and type:	23	18	26	27	47	12	5	19	20	96
Biomass (natural draft)	22	11	23	24	42	9	5	10	8	75
Biomass (forced draft)	1	0	0	6	4	0	0	1	0	9
Charcoal	6	7	11	15	19	6	1	6	3	42
LPG	8	11	15	11	19	7	2	6	5	41
Kerosene	5	12	12	11	13	6	0	4	4	36
Electric	5	7	8	4	3	5	0	5	1	18
Region										
Latin America & Caribbean	3	1	3	4	14	2	0	3	6	28
North Africa & Middle East	0	0	0	0	1	2	0	2	1	6
Sub-Saharan Africa	8	8	11	8	8	8	3	8	11	46
South Asia	15	13	12	10	15	8	6	7	8	48
East Asia & Pacific	0	1	0	2	6	3	1	3	1	13
Other Asia (Southeast, Central)	0	3	1	3	4	4	0	7	6	24
Global	0	1	1	1	6	16	1	2	7	27
Other/N.A.	1	1	2	4	3	6	0	8	1	27
Year of article publication										
Before 2000	2	4	2	3	3	3	3	6	2	22
2000–2009	9	8	7	15	28	19	5	18	14	82
2010–2016	15	13	18	9	18	16	3	10	15	74
Total	26	25	27	27	49	38	11	34	31	178

Notes: The search covered articles published up to the year 2016. Several types of parameters can be sourced from any given article; the number of unique articles included in the database is 177.

Following model parameterization, we adapted a Monte Carlo simulation approach to calculate net benefits (Whittington et al., 2009). The purpose of the simulation procedure is to allow parameters to vary randomly such that each trial (out of 10,000 that we run in total) is based on a unique combination of parameters. Because the parameters have been sourced from the literature, we believe that the outcome distributions reflect the variation that is likely to exist in developing countries. Yet we emphasize that the frequency with which any specific combination of parameter values – or net benefit outcomes – would arise is unknown. As a result, these cumulative distributions should not be interpreted to represent the precise distribution of real-world outcomes.

3. Results and discussion

3.1. Deterministic comparison of benefits and costs

Fig. 1A compares the three definitions of net benefits across ICS types calculated using average parameter values. Because we incorporate applied research that offers a more nuanced perspective on the realized benefits of ICS, our results are somewhat different from those obtained in prior deterministic cost-benefit analyses. In particular, private net benefits for several ICS (both biomass ICS, and kerosene and LPG) are negative, and those for an electric stove are close to zero. Not surprisingly, inclusion of all social benefits increases the net benefits of all options, though the net benefits of kerosene remain strongly negative. The size of the environmental externalities of inefficient cooking has perhaps been underappreciated in prior analyses (Jeuland and Pattanayak, 2012), especially when the set of pollutants considered goes beyond those included in the Kyoto protocol (Myhre et al., 2013). These results reflect the important role of BC, which on average outweighs reductions in co-emitted OC (a net cooling agent) and the increases in other climate-forcing from the use of processed fuels.

Decomposition of these net results makes clear that for most technologies, the benefits from reducing climate forcing, which do not accrue to stove users, are the largest category of benefits (Fig. 1B). It also demonstrates that emissions reduction externalities of LPG and kerosene cooking are greatest, despite the fact that these utilize fossil fuels. Only for the charcoal ICS and electric ICS do the climate mitigation benefits represent a minority of the total; these two technologies rely on use of fuels that usually require CO_2-intensive production, and they also provide greater fuel cost and time savings than other solutions. In all cases, health improvements represent a relatively small amount of total benefits. Finally, in the social analysis, monthly stove costs are weighted less heavily than in the private analysis, because the social discount rate is lower than the private one, which reflects the reality that low-income beneficiaries of cooking interventions are often strongly present-minded (Beltramo et al., 2015).

3.2. Evidence from the Monte Carlo simulations

The previous results (with mean global parameter values) are not representative of the wide range of possible or likely outcomes in the real world, however. Our simulation results provide a more complete comparison. Here we discuss the results in detail that follow from the model analysis that includes all assumed parameter correlations; outcomes are not substantively different if we remove correlations, though the distributions are somewhat broader (Table S1).

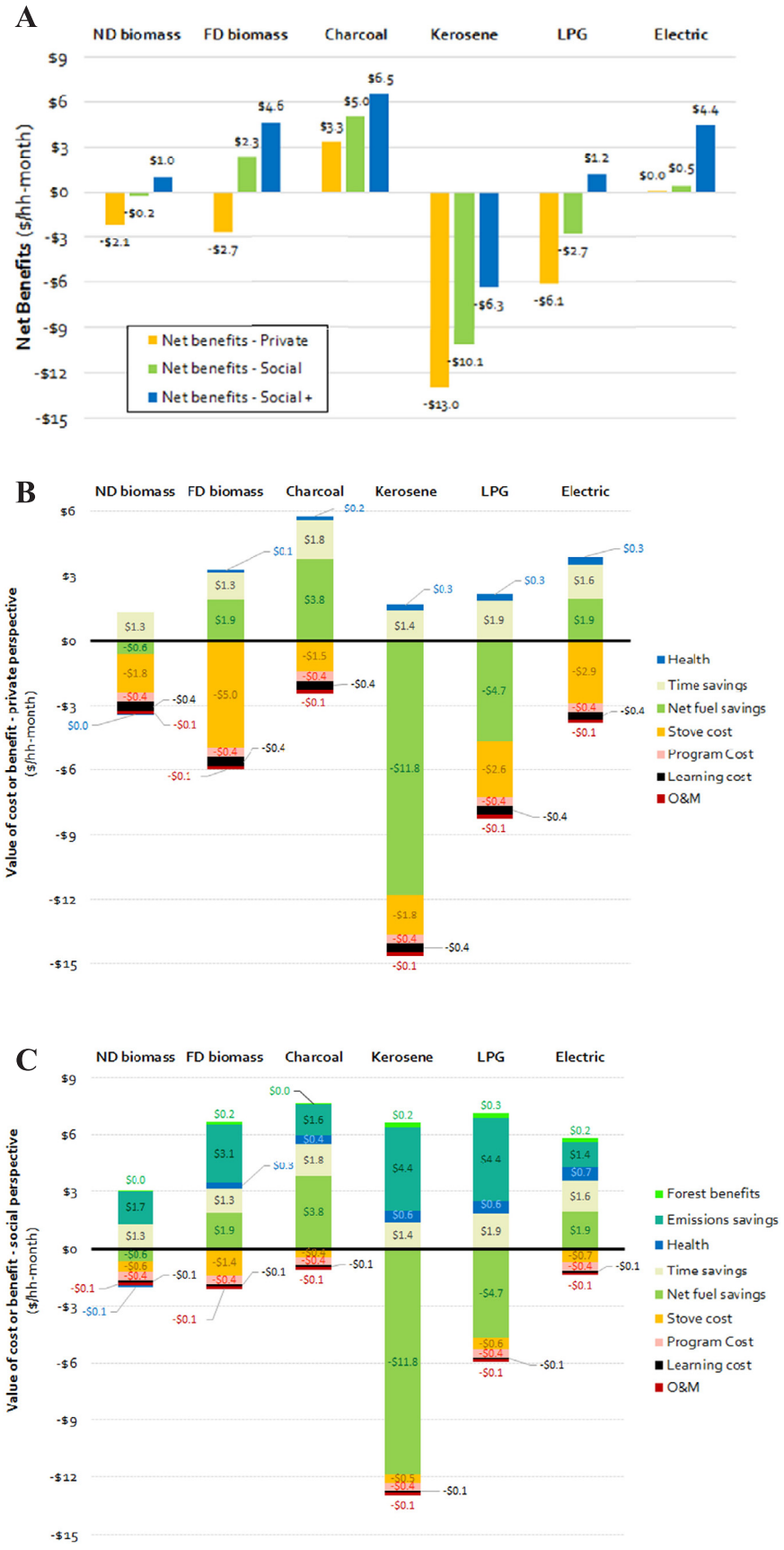

Fig. 1. Panel A: Change in net benefits for the six ICS options under private and social perspectives. Panel B: Composition of net benefits for the six ICS options under private perspective. Panel C: Composition of net benefits for the six ICS options under social + perspective. (*Notes*: All parameters are set to global mean values; charcoal is from a traditional charcoal stove, and all others are from traditional biomass; emissions savings include all major climate-altering pollutants, as described in the text).

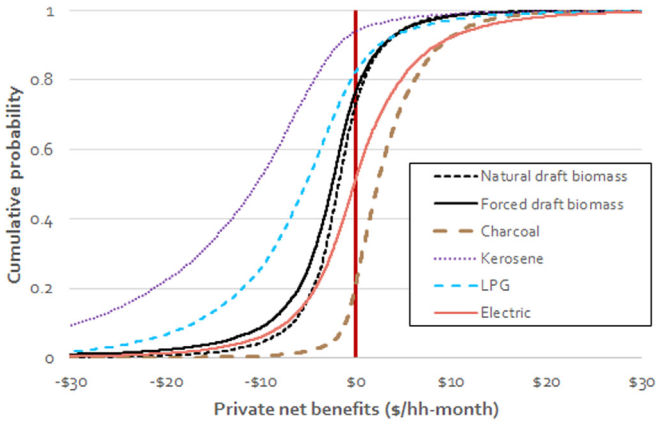

Fig. 2. Cumulative distributions for net private benefits of transitions to ICS (*Note*: Charcoal is from a traditional charcoal stove, and all others are from traditional biomass).

3.2.1. Private net benefits

Fig. 2 shows the simulated cumulative distribution functions of private net benefits for the six ICS transitions. One ICS option – charcoal – delivers positive net benefits in over half of the simulation trials, in 79% of realizations. Kerosene has the highest percentage of negative outcomes (94%), while LPG and electric ICS each have negative outcomes in about 52% and 83% of trials, respectively. The biomass-burning stoves also have a large proportion of negative NPV outcomes, with 73% and 77% for the natural and forced draft options. There would thus appear to be many circumstances in which households do not benefit from switching to improved technologies, which perhaps explains why observed take-up is often low. In addition, one-way sensitivity analyses for each model parameter reveal that the factors that most influence variability in private benefits tend to be related to ICS fuel efficiencies, time savings and expenses, ICS use, ICS and fuel costs, the value of time, and the private discount rate (Fig. 3). Consistent with literature that suggests that health benefits of ICS interventions may be modest or low when use is partial (Mortimer et al., 2017; Simon et al., 2014), most of the health-related parameters play only a modest role in affecting net benefits.

The use rates for improved cooking technologies that are reported in the literature vary greatly and represent an important potential optimizing margin, so we next systematically varied these while running the simulations. For most ICS options, mean private net benefits are a weakly increasing function of use, except for LPG and kerosene, for which marginal fuel costs somewhat outweigh the marginal benefits from increased use (Fig. S1). Kerosene stoves mostly produce negative benefits across use levels. Furthermore, mean outcomes remain negative across nearly all use levels for the LPG and biomass stoves, and the 10th–90th percent confidence intervals across increase in size as a function of use. Across use levels, these confidence intervals span from positive to negative net benefits for all but the charcoal ICS, which tends towards more positive values. Adjustment on the intensive margin of stove use does not necessarily allow households to produce net benefits, unless they are already using a costly fuel (such as charcoal).

3.2.2. Social net benefits

The results are very different when all environmental and health externalities (the social+ analysis) are included, with all ICS producing net benefits in the majority of simulation trials (Fig. 4). Charcoal and electric ICS perform best (with 99% and 84% positive outcomes), followed by most of the other stoves (74–82%), except kerosene (only 54% positive outcomes). The distribution for kerosene has a much thicker downside tail, mostly because of higher fuel costs. Ignoring climate impacts of non-Kyoto emissions leads to substantially worse results (Fig. S2), especially for the electric stove because of higher electricity generation emissions. A scenario with clean electricity, however, shifts the electric stove distributions strongly to the right (beneficially), well past that for charcoal (Fig. S3). For social benefits, one-way sensitivity analyses for each model parameter reveal that the factors that most influence variability in net benefits continue to be ICS fuel efficiencies, the value of time and time savings, and ICS use, but now also include

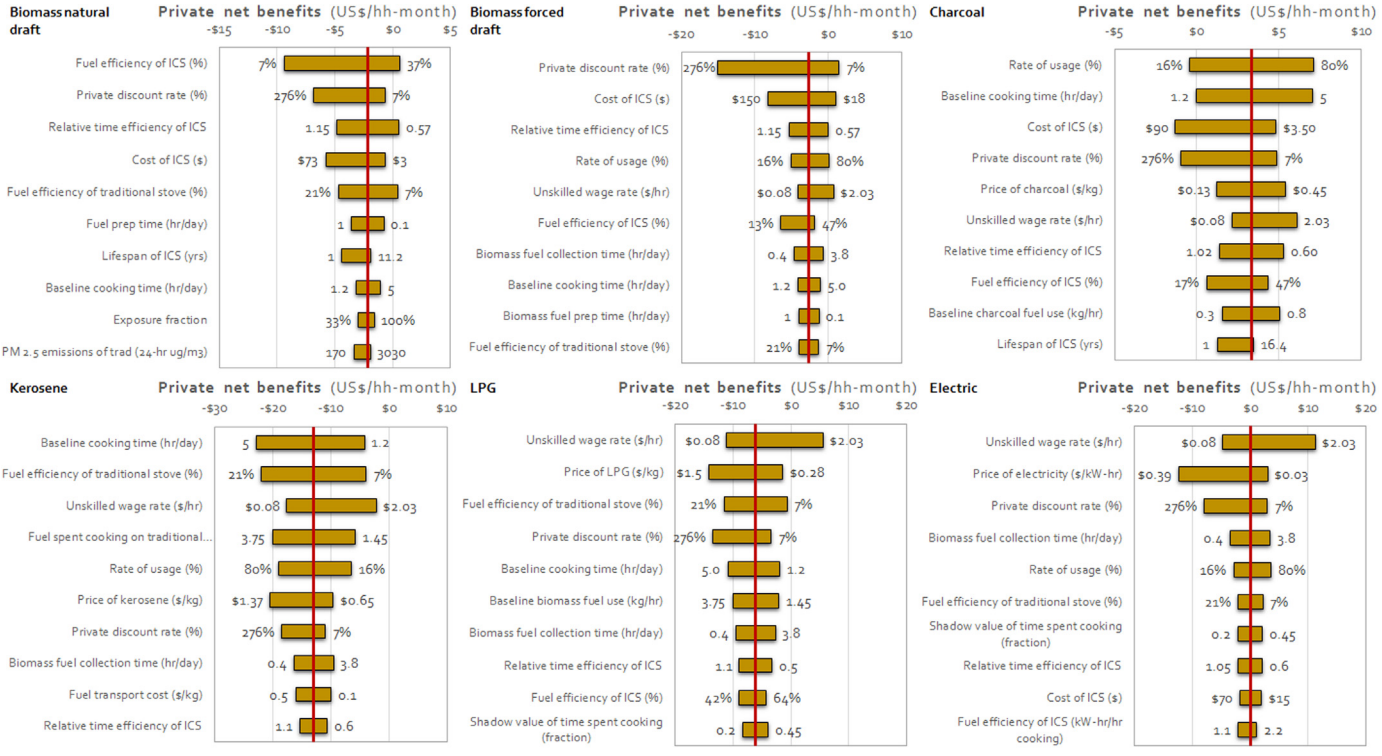

Fig. 3. Sensitivity analyses of private net benefits.

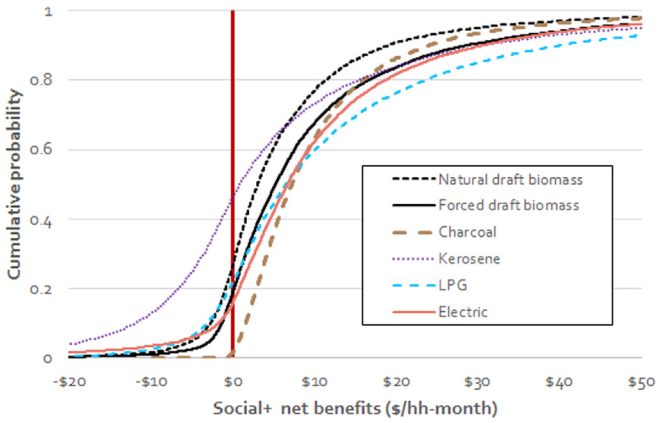

Fig. 4. Cumulative distributions for net social+ benefits of transitions to ICS (*Note*: Charcoal is from a traditional charcoal stove, and all others are from traditional biomass).

the cost of carbon (climate damages) and emission rates for climate-altering pollutants, about which there is great uncertainty (Fig. S4). Importantly, unlike private net benefits, social net benefits always increase with use, which points to the need to find instruments that shift more than just uptake of ICS.

The differences between the private and social+ analyses are due to the inclusion of benefits from modest health spillovers, reduced deforestation, and climate-forcing. As shown, these benefits – and primarily those from climate mitigation – dramatically change the economic calculations. This provides motivation for exploring more carefully how incentives delivered to households – in the form of stove or fuel subsidies – might facilitate the transition to cleaner options.

3.3. Analysis of subsidies

Despite the fact that subsidies can be an effective instrument for promoting behavioral change (Volpp et al., 2009), including for encouraging improved adherence to medical treatment (McCoy et al., 2017), research related to their impact on cleaner cooking is rather limited.[7] This has not prevented their deployment as a policy instrument. For example, the Indonesian government concurrently increased subsidies for LPG fuel and stoves, while reducing subsidies for kerosene, in an attempt to motivate a transition to LPG (Budya and Arofat, 2011). Ecuador has achieved high rates of LPG penetration with generous subsidies (Troncoso and da Silva, 2017), and India's new program expanding gas subsidies is similarly aiming to spur a cooking transition there (Mittal et al., 2017). In our final analyses, we build on the simulations discussed above to more systematically understand how behavioral incentives might change in response to subsidy instruments. Specifically, we investigate how the distributions of private benefits (i.e., the private rationale for ICS use) are affected by fuel and stove price discounts that reduce private household costs. We express these subsidies in terms of percentages of the total stove and fuel cost, respectively. We also include all technology types for completeness, though we note that fuel subsidies would clearly not be viable for incentivizing charcoal and biomass-burning ICS (as these would incentivize greater use of inefficient technology).

This analysis is conducted from the private household perspective; the social NPV would be unchanged by this transfer except insofar as these subsidies have broader economic costs. As far as we know, the latter have not previously been quantified in the context of subsidies aimed at incentivizing clean cooking. It is important to note, however, that commentaries and more general economic work suggests that the efficiency costs of fuel subsidies in particular are substantial (Lin and Jiang, 2011; Rao, 2012). In the context of clean cooking, concerns about targeting and rebound effects on energy use would create significant implementation challenges.

Several observations emerge from this analysis. First, stove purchase subsidies only lead to a high likelihood of positive private net benefits for the forced draft biomass (in 69% of trials for full (100%) stove subsidies) and the electric (74%) ICS (Fig. 5), which are relatively costly to purchase. The implication is that even full ICS cost subsidies may be insufficient to achieve socially desirable uptake and use rates. Second, for stoves requiring kerosene, LPG and electricity, fuel subsidies have a major positive effect in shifting the distributions of private benefits positively (with 48%, 56% and 78% of trials yielding positive NPV, respectively, for full fuel subsidies, and relatively modest negative outcomes). Still, these levels of uptake and private benefits remain well below socially optimal levels. Third, exploring the potential role for adjustment on the use margin given higher subsidies, we see that increased use would only generally allow positive private net benefits for the electric ICS (Fig. S5). The confidence intervals for all other ICS span the negative to positive range across use levels. Electric ICS' are thus most responsive to both fuel and stove subsidies, but subsidizing electricity is also much more complicated due to its alternative uses and the likely behavioral responses that would result. Indeed, one major conclusion of this analysis is that what is really needed to shift behavior is an incentive that would reward use of clean options, or alternatively tax the use of polluting traditional ones.

4. Conclusions and policy implications

Policymakers, perhaps cognizant of the significant climate damages and other ills attributed to traditional cooking, have pushed for a revival in ICS promotion interventions. Yet interventions are often still designed and implemented based on the assumption that households will readily choose to use efficient stoves extensively, once these are provided. By combining empirical evidence from various literatures, we conducted extensive cost-benefit analysis of household transitions to various types of cleaner cooking technologies that calls for careful consideration of whether this basic assumption will generally hold.

Our results demonstrate that households may not typically benefit privately from a switch to these technologies: Even if we assume that health and time savings gains are fully internalized, simulated private net benefits for ICS use are more often negative than not. The primary exception to this is for a transition by charcoal-using households to more efficient technology, which is the transition that is most relevant to urban or peri-urban households in sub-Saharan Africa. Electric ICS perform next best from a private perspective, but these require a reliable electricity connection, which is hardly a given in most energy-poor settings globally. In contrast, net benefits are almost always positive when the environmental benefits and reduced climate forcing related to BC and co-emissions are included in the accounting ledger. This is true for transitions to LPG, charcoal, electric, and most improved biomass stoves, especially when power generation for electricity is clean. Given that environmental and climate benefits do not accrue to those adopting these technologies, it is unlikely that households will account for these benefits in their decision calculus. This will result in underinvestment in ICS, a problem that could perhaps be corrected using subsidies.

Thus, we go on to investigate the role that fuel and stove subsidies could play in altering households' private net benefits from ICS adoption and usage. Such subsidies do considerably shift the net benefits distributions to the right, but their relative effectiveness depends greatly on the type of stove and fuel being considered. Stove subsidies are most effective for expensive options such as forced draft biomass ICS and electric ICS, while fuel subsidies are most effective for the

[7] Several new studies have experimentally tested their effects on the initial uptake of ICS technologies in a number of settings (Beltramo et al., 2015; Levine et al., 2018; Pattanayak et al., 2018). Noting that initial uptake does not guarantee sustained use, a recent pilot study in Cambodia also explored the short-term effects of use incentives (Usmani et al., 2017).

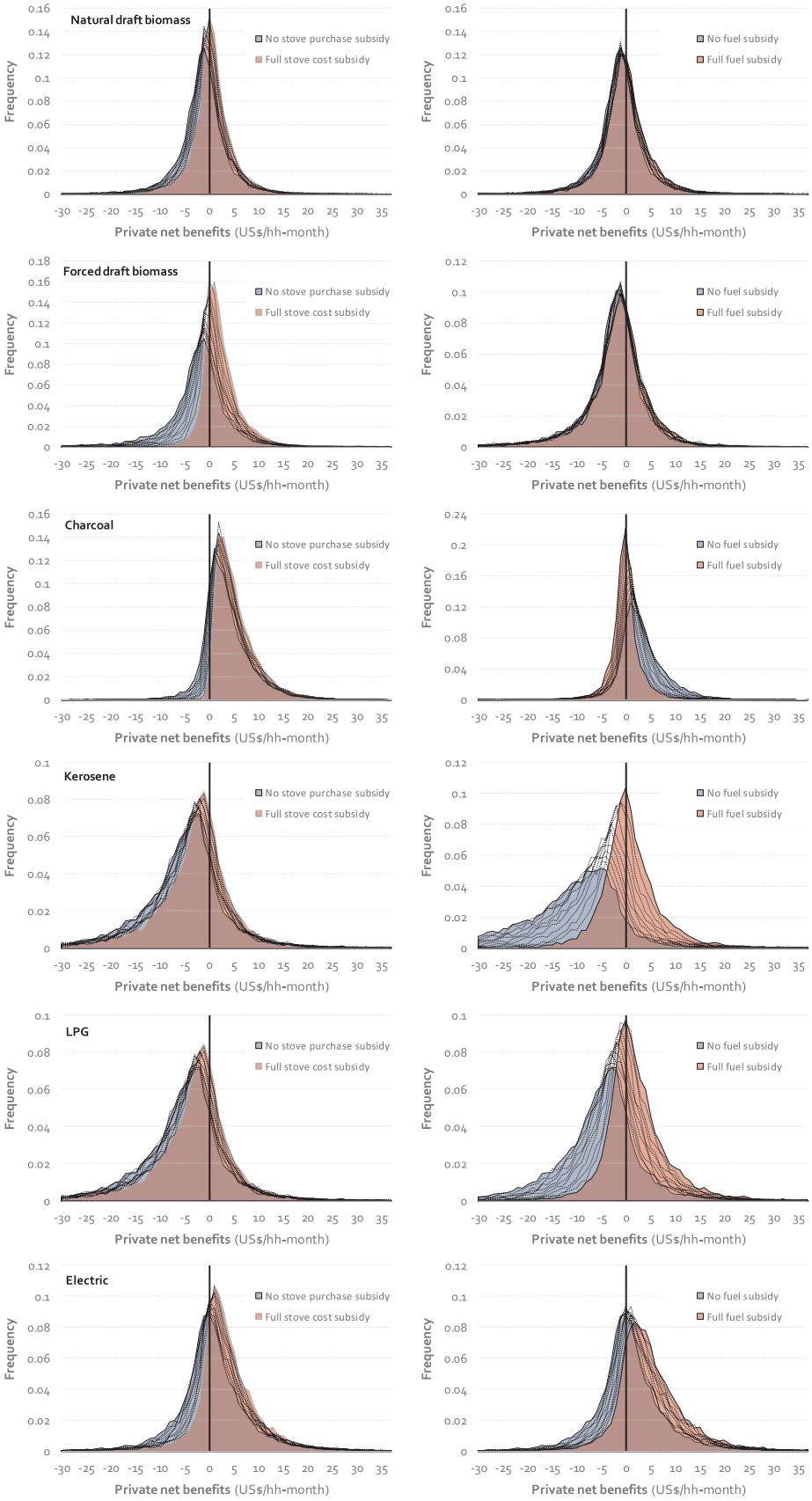

Fig. 5. Effects of stove purchase and fuel subsidies on distribution of net private benefits (*Notes*: Charcoal is from a traditional charcoal stove, and all others are from traditional biomass; thin dotted lines refer to the family of distributions generated by increasing the fraction of subsidy by 10% at a time).

options that rely on modern or non-biomass fuels. Perhaps just as importantly, though, even full subsidies may be insufficient to achieve general adoption of cleaner cooking technologies among utility-maximizing households, even once we allow for adjustment on the intensive margin of adoption.

It is important to repeat the caveat that the frequency with which any specific combination of parameter values and net benefit outcomes would arise in real world interventions is unknown. Indeed, several limitations of our analysis deserve mention. A first important concern is that of site- or technology-selection bias (Allcott, 2015): Research may focus on the most promising or the most difficult examples and settings, and so, we may misrepresent outcomes because our model assumptions do not sufficiently cover typical implementation experiences. Given this important caveat, we believe that it remains important for researchers to publish site-specific CBAs of ICS interventions that would complement the systematic look provided here (Pant et al., 2014; Pinto, 2016), and highlight the particular features of successes or failures. Second, some issues are rarely studied in quantitative or economic terms (e.g., valuation of local loss of forest cover, stove maintenance or promotion program costs) and thus require us to apply parameter values measured in a handful of likely unrepresentative studies. Third, because studies do not always measure a particular construct in the same way, or in a manner that is consistent with our general model structure, we are not always able to take advantage of the entire body of knowledge available in the literature. Continued standardization of measures and alignment with policy needs (e.g., for calculating costs and benefits) should be an objective of continued research in this domain.

These caveats notwithstanding, our results provide a starting point for decision makers confounded by past failures in ICS promotion, by pointing to policy instruments – stove and fuel subsidies, carbon finance, or conditional cash transfers or rebates – that can and should be deployed to encourage use of cleaner cooking technologies, including biomass ICS, for which fuel subsidies in particular are not possible. Of course, subsidy design is challenging, and stimulating use need not happen strictly through subsidies. Building on significant progress achieved recently, continued support to R&D efforts to create better and more user-centered technology (Jeuland et al., 2014; Shan et al., 2017), would likely also help. Standards and results of field-testing could also be encouraged to better identify which technologies really provide private and social benefits, and these results should continue to be disseminated to improve decision-making. But we take the opportunity to reemphasize that technology acquisition alone is insufficient to produce benefits, and that there is at least as great a need to stimulate *usage* as there is to subsidize *purchase* of efficient technologies, if these social benefits of clean cooking are to be realized. Our data-driven approach, which reveals significant influence of behavioral parameters and the lack of clear private net benefits to households, echoes warnings in the literature that highlight the dearth of knowledge on how to overcome partial or short-lived usage (Brooks et al., 2016; Masera et al., 2000). Effective and appropriate incentive design is also challenging, however, and capture by individuals who do not need them or unintended negative (e.g., rebound) effects that increase environmental harms could occur. We therefore close with a call for more scientific research on implementation research to deliver technologies that are socially beneficial, and incentives that stimulate use of clean cooking technologies, while also minimizing potential negative consequences. This is particularly vital considering households' deeply ingrained cooking-related cultural and taste preferences.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.enpol.2018.06.031.

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